CLAIMS

What is claimed is:

1. A method of determining characteristics of an earth formation traversed by a borehole, the method comprising:

transmitting acoustic energy into the earth formation from within the borehole;

receiving at least some of the acoustic energy to create a plurality of received waveforms;

estimating source waveforms from the received waveforms to create estimated source waveforms; and

comparing the estimated source waveforms to determine a characteristic of the earth formation.

2. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 1 wherein transmitting acoustic energy into the earth formation from within the borehole further comprises transmitting acoustic energy from an acoustic source mounted on a tool disposed within the borehole.

3. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 2 wherein transmitting acoustic energy from an acoustic source mounted on a tool disposed within the borehole further comprises transmitting acoustic energy from an acoustic source mounted on a wireline logging tool.

4. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 2 wherein transmitting acoustic energy from an acoustic source mounted on a

tool disposed within the borehole further comprises transmitting acoustic energy from an acoustic source mounted on a logging while drilling tool.

5. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 1 wherein receiving at least some of the acoustic energy to create a plurality of received waveforms further comprises:

receiving acoustic energy at a first receiver mounted on a tool disposed within the borehole to create a first received waveform; and

receiving acoustic energy at a second receiver mounted on the tool disposed within the borehole to create a second received waveform.

6. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 5 wherein receiving acoustic energy at the first and second receiver mounted on the tool further comprises receiving acoustic energy at the first and second receivers mounted on a wireline logging tool.

7. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 5 wherein receiving acoustic energy at the first and second receiver mounted on the tool further comprises receiving acoustic energy at the first and second receivers mounted on a logging while drilling tool.

8. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 1 wherein estimating source waveforms from the received waveforms to

create estimated source waveforms further comprises:

estimating a transfer function of the earth formation; and

applying each of the plurality of received waveforms to the inverse transfer function to create the estimated source waveforms.

9. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 8 wherein estimating a transfer function of the earth formation further comprises estimating a slowness of the formation of the acoustic energy.

10. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 9 wherein estimating a transfer function of the earth formation further comprises estimating an attenuation experienced by the acoustic energy through the formation.

11. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 1 wherein comparing the estimated source waveforms to determine a characteristic of the earth formation further comprises determining a value of an objective function based on the estimated source waveforms.

12. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 11 wherein determining a value of an objective function based on the estimated source waveforms further comprises determining a variance value of the estimated source waveforms.

13. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 12 wherein determining a variance value of the estimated source waveforms further comprises calculating the variance value using substantially the following equations:

$$\delta^2 = \sum_{i=1}^{N} (S_{EST_i}(t) - S_{EST_{AVG}}(t))^2$$

where δ^2 is the variance value, S_{EST_i} is a source waveform estimated for each received waveform, $S_{EST_{AVG}}$ is the average estimated source waveform calculated using substantially the following equation:

$$S_{EST_{AVG}}(t) = \frac{1}{N}\sum_{i=1}^{N} S_{EST_i}(t)$$

where N is the number of received waveforms, and t is time

14. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 13 wherein comparing the estimated source waveforms to determine a characteristic of the earth formation further comprises:

repeating the estimating source waveforms step, and for each set of estimated source waveforms, calculating the variance value; and

plotting each variance value as a function of a starting time and an estimated slowness in an assumed transfer function.

15. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 14 further comprising determining the characteristic of the earth formation by searching for minimas of the plot of the variance values.

16. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 15 further comprising estimating an error in the determination of the characteristic of the earth formation based on the variance value at the minima.

17. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 15 further comprising estimating an error in the determination of the characteristic of the earth formation based on a curvature of the plot at the minima.

18. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 11 wherein determining a value of an objective function based on the estimated source waveforms further comprises calculating the value of the objective function by summing a difference between each successive estimated source waveform.

19. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 18 wherein calculating the value of the objective function by summing a difference between each successive estimated source waveform further comprises application of substantially the following equation:

$$\zeta = \sum_{i=1}^{N-1} (\mathbf{S}_{\mathbf{EST}_{i+1}} - \mathbf{S}_{\mathbf{EST}_i})^2$$

where ζ is the value of the objective function, S_{EST_i} is a source waveform estimated for each received waveform, and N is the number of received waveforms.

20. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 19 wherein comparing the estimated source waveforms to determine characteristics of the earth formation further comprises:

repeating the estimating source waveforms step, and for each set of estimated source waveforms, calculating the value of the objective function; and.

plotting the values of the objective function as a function of starting time and estimated slowness in the assumed transfer function.

21. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 20 further comprising determining the characteristic of the earth formation by searching for minimas of the plot of the objective function values.

22. The method of determining characteristics of an earth formation traversed by a borehole as defined in claim 21 further comprising estimating an error in the determination of the characteristic of the earth formation based a curvature of the objective value plot at the minima.

23. A method of operating a tool disposed within a borehole traversing an earth formation, the method comprising:

directing acoustic energy into the formation;

generating received waveforms responsive to the acoustic energy as it propagates in the formation;

estimating source waveforms based on the received waveforms; and

comparing the estimated source waveforms to determine acoustic velocity of the earth

formation.

24. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 23 wherein comparing the estimated source waveforms to determine acoustic velocity of the earth formation further comprises:

calculating an objective function based on the estimated source waveforms; and

determining the acoustic velocity of the earth formation based on a plot containing the objective function.

25. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 24 wherein calculating an objective function based on the estimated source waveforms further comprises:

averaging the estimated source waveforms to determine an average estimated source waveform; and

determining a variance value of the estimated source waveforms using the average estimated source waveform, the variance value being the objective function.

26. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 25 wherein averaging the estimated source waveforms to determine an average estimated source waveform further comprises determining the average estimated source waveform using substantially the following equation:

$$S_{EST_{AVG}}(t) = \frac{1}{N}\sum_{i=1}^{N} S_{EST_i}(t)$$

where $S_{EST_{AVG}}$ is the average estimated source waveform, N is the number received waveforms, S_{EST_i} is the estimated source received waveform, and t is time.

27. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 26 wherein determining a variance value of the estimated source waveforms using the average estimated source waveform further comprises calculating the variance value using substantially the following equation:

$$\delta^2 = \sum_{i=1}^{N} (S_{EST_i}(t) - S_{EST_{AVG}}(t))^2$$

where δ^2 is the variance, $S_{EST_{AVG}}$ is the average estimated source waveform, N is the number of received waveforms, S_{EST_i} is the estimated source received waveform, and t is time.

28. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 25 further comprising:

plotting multiple variance values calculated for multiple sets of estimated source waveforms to create a plot; and

determining inflection points of the variance values within the plot as indicative of acoustic velocity within the earth formation.

29. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 28 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises finding locations in the plot where the inflection points are minimas.

30. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 29 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises determining an error in the acoustic velocity determination proportional to the value of the objective function at the minimas.

31. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 24 wherein calculating an objective function based on the estimated source waveforms further comprises calculating a differential objective function using substantially the following equation:

$$\zeta = \sum_{i=1}^{N-1} (\mathbf{S}_{\mathbf{EST}_{i+1}} - \mathbf{S}_{\mathbf{EST}_i})^2$$

where ζ is the differential objective function, and N is the number of received waveforms, and S_{EST_i} is the estimated source waveform for each received waveform.

32. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 31 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises:

plotting multiple values of the differential objective function calculated for multiple sets of estimated source waveforms to obtain a plot; and

determining inflection points of the values of the differential objective function within the plot as indicative of acoustic velocity within the earth formation.

33. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 32 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises finding locations in the plot where the inflection points are minimas.

34. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 23 directing acoustic energy into the formation further comprises directing acoustic energy into the formation from a wireline logging tool.

35. The method of operating a tool disposed within a borehole traversing an earth formation as defined in claim 23 directing acoustic energy into the formation further comprises directing acoustic energy into the formation from a logging while drilling tool.

36. In a system with a logging tool disposed within a borehole, the borehole traversing an earth formation, and with the logging tool having a transmitter and a plurality of receivers spaced apart from the transmitter and from each other, a method of determining a characteristic of the earth formation comprising:

transmitting acoustic signals into the earth formation with the transmitter;

receiving the acoustic signals with the plurality of receivers to create receiver signals;

estimating a source wavelet for each of the plurality of receiver signals to create a plurality of estimated source wavelets; and

determining acoustic velocity of the earth formation by comparison of the plurality of estimated source wavelets.

37. The method of determining a characteristic of the earth formation as defined in claim 36 wherein estimating a source wavelet for each of the plurality of receiver signals to create a plurality of estimated source wavelets further comprises:

estimating a transfer function of the formation; and

calculating the estimated source signals by applying the inverse transfer function to each of the receiver signals.

38. The method of determining a characteristic of the earth formation as defined in claim 37 wherein determining acoustic velocity of the earth formation by comparison of the plurality of estimated source wavelets further comprises calculating an objective function based on the plurality of estimated source wavelets.

39. The method of determining a characteristic of the earth formation as defined in claim 38 wherein calculating an objective function based on the plurality of estimated source wavelets further comprises determining a variance of the estimated source wavelets.

40. The method of determining a characteristic of the earth formation as defined in claim 39 wherein determining a variance value or the estimated source wavelets further comprises calculating the variance value using substantially the following equations:

$$\delta^2 = \sum_{i=1}^{N} (S_{EST_i}(t) - S_{EST_{AVG}}(t))^2$$

where δ^2 is the variance value, S_{EST_i} is the estimated source wavelet for each receiver waveform,

$S_{EST_{AVG}}$ is an average estimated source wavelet calculated using substantially the following equation:

$$S_{EST_{AVG}}(t) = \frac{1}{N}\sum_{i=1}^{N} S_{EST_i}(t)$$

where N is the number of receiver signals, and t is time

41. The method of determining a characteristic of the earth formation as defined in claim 40 wherein determining acoustic velocity of the earth formation by comparison of the plurality of estimated source wavelets further comprises:

repeating the estimating source wavelets step, and for each set of estimated source wavelets, calculating the variance value; and

plotting each variance value at least as a function of slowness to create a variance value plot.

42. The method of determining a characteristic of the earth formation as defined in claim 41 further comprising determining the characteristic of the earth formation by searching for minimas of the variance value plot.

43. The method of determining a characteristic of the earth formation as defined in claim 42 further comprising estimating an error in the determination of the characteristic of the earth formation based on a curvature of the variance value plot at the minima.

44. The method of determining a characteristic of the earth formations as defined in claim 43 wherein receiving acoustic signals with the plurality of receivers to create receiver signals further

comprises receiving the acoustic signals on a wireline logging tool.

45. The method of determining a characteristic of the earth formations as defined in claim 43 wherein receiving acoustic signals with the plurality of receivers to create receiver signals further comprises receiving the acoustic signals on a logging while drilling tool.

46. The method of determining a characteristic of the earth formation as defined in claim 38 wherein calculating an objective function based on the plurality of estimated source wavelets further comprises calculating a difference between estimated source wavelets.

47. The method of determining a characteristic of the earth formation as defined in claim 46 wherein calculating a difference between estimated source wavelets further comprises use of substantially the following equation:

$$\zeta = \sum_{i=1}^{N-1} (\mathbf{S}_{EST_{i+1}} - \mathbf{S}_{EST_i})^2$$

where ζ is a value of the objective function, S_{EST_i} is the estimated source wavelet for each receiver signal, and N is the number of receiver signals.

48. The method of determining a characteristic of the earth formation as defined in claim 47 wherein determining acoustic velocity of the earth formation by comparison of the plurality of estimated source wavelets further comprises:

repeating the estimating source wavelets step, and for each set of estimated source wavelets, calculating the value of the objective function; and

plotting the values of the objective function at least as a function of slowness to create a differential value plot.

49. The method of determining a characteristic of the earth formation as defined in claim 48 further comprising determining the characteristic of the earth formation by searching for minimas of the differential value plot.

50. The method of determining a characteristic of the earth formation as defined in claim 49 further comprising estimating an error in the determination of the characteristic of the earth formation based a curvature of the differential value plot at the minima.

51. The method of determining a characteristic of the earth formations as defined in claim 50 wherein receiving acoustic signals with the plurality of receivers to create receiver signals further comprises receiving the acoustic signals on a wireline logging tool.

52. The method of determining a characteristic of the earth formations as defined in claim 50 wherein receiving acoustic signals with the plurality of receivers to create receiver signals further comprises receiving the acoustic signals on a logging while drilling tool.

53. A method of determining slowness of an earth formation comprising:

a) generating acoustic signals with a transmitter mounted on a tool disposed within a borehole traversing the earth formation;

b) receiving at a first receiver mounted on the tool acoustic energy to create a first

receiver signal;

c) receiving at a second receiver mounted on the tool acoustic energy to create a second receiver signal;

d) estimating a transfer function that comprises an assumed slowness of the earth formation;

e) calculating a first source wavelet using the first receiver signal and the estimated transfer function, the calculating beginning at a time based on a start time;

f) calculating a second source wavelet using the second receiver signal and the estimated transfer function, the calculating beginning at a time based on the start time;

g) comparing the first and second source wavelets to obtain an objective function;

h) plotting the objective function as a function of slowness of the assumed transfer function on a first axis and the start time of steps e) and f) on a second axis;

i) repeating steps d) through h) for a plurality of assumed transfer functions;

j) repeating steps d) through i) for a plurality of start times;

k) finding inflection points in the plot of the objective function, where the location of the inflection points on the first axis indicate the formation slowness.

54. The method of determining slowness of an earth formation as defined in claim 53 wherein comparing the first and second source wavelets to obtain an objective function further comprises:

calculating an average estimated source wavelet; and

calculating a variance using the first and second source wavelets and the average estimated source wavelet.

55. The method of determining slowness of an earth formation as defined in claim 54 wherein calculating the average estimated source wavelet further comprises calculating the average estimated source wavelet using substantially the following equation:

$$S_{EST_{AVG}}(t) = \frac{1}{N}\sum_{i=1}^{N} S_{EST_i}(t)$$

where $S_{EST_{AVG}}$ is the average estimated source wavelet, N is the number of calculated source wavelets, S_{EST_i} is the source wavelets, and t is time.

56. The method of determining slowness of an earth formation as defined in claim 55 wherein calculating a variance using the first and second source wavelets and the average estimated source wavelet further comprises calculating the variance using substantially the following equation:

$$\delta^2 = \sum_{i=1}^{N} (S_{EST_i}(t) - S_{EST_{AVG}}(t))^2$$

where δ^2 is the variance.

57. The method of determining slowness of an earth formation as defined in claim 53 wherein comparing the first and second source wavelets to obtain an objective function further comprises determining a difference between the source wavelets as the objective function.

58. The method of determining slowness of an earth formation as defined in claim 57 wherein determining a difference between the source wavelets further comprises calculating an

objective function using substantially the following equation:

$$\zeta = \sum_{i=1}^{N-1} (S_{EST_{i+1}} - S_{EST_i})^2$$

where ζ is the objective function, S_{EST_i} is the source wavelets, and N is the number of calculated source wavelets.